GLAS Atmospheric Data Products Validation Plan

GLAS Atmosphere Group

Steve Palm[1], Dennis Hlavka and Bill Hart
Science Systems and Applications Inc
Lanham, MD

Jim Spinhirne
Goddard Space Flight Center
Greenbelt, MD

Ellsworth J. Welton
Goddard Earth Science Technology Center
University of Maryland, Baltimore County

Version 2
September, 2000

[1]Corresponding Address: Code 912, Goddard Space Flight Center, Greenbelt, MD 20771
Email: spp@virl.gsfc.nasa.gov

TABLE OF CONTENTS

1.0 INTRODUCTION …………………………………………………………….…………1

1.1 Scientific Objectives ……..……..………………………………………………….1
1.2 Missions………………………….…………………………….……….……………2
1.3 Validation Requirements …….…………………………..…..……….…...……………….. 2

2.0 SCIENCE DATA PRODUCTS ………………………...…………………………… 3
2.1 Expected Accuracy and Limitations …..……………………………………………….. 4
2.1.1 Calibrated Atmospheric Backscatter ……..……………………………….. 5
2.1.2 Cloud and Aerosol Layer Heights ……….……………………...………. 6
2.1.3 Cloud and Aerosol Layer Optical Depth ……………..…………..………….. 7

3.0 VALIDATION CRITERIA ……………………………………………………… 10

3.1 Overall Approach ………………………………………………………..……… 10
3.1.1 Pre-Launch …………………………………………………………. 10
3.1.2 Post-Launch ………………………………...……….………………. 11
3.2 Sampling Requirements …………………………..………………………...……12
3.3 Measures of Success ………………………………………….…………….……. 13

4.0 PRE-LAUNCH ACTIVITIES …………………………………………………… 14

4.1 Field Experiments and Studies …………………………………………………….. 14
4.2 Operational Surface Networks………………………………………………….. 15
4.2.1 AERONET ….…………………………………….……………… 15
4.2.2 MPLNet …….…………………………….….………………… 17
4.2.3 EARLINET ….…………………………….………………………... 18
4.2.4 Asian Dust Observing Network …………………….………………… 19
4.3Existing Satellite Data ……………………...……………………………... 20

5.0 POST-LAUNCH ACTIVITIES ..…………………………...………………..20

5.1 Planned Field Activities and Studies………….………..………..……….. 20
5.2 New EOS-targeted Field Campaign.………….………..……………………. 22
5.3 Needs for Other Satellite Data …..……..…..……….....……………..……. 24
5.4 Measurement Needs at Calibration/Validation Sites …..……..……….……. 25
5.5 Needs for Instrument Development …….…………………..………………..……. 25
5.6 Geometric Registration Site………………………..…………...……….. 26
5.7 Intercomparisons ……………………..……………….……………….. 26

6.0 IMPLEMENTATION OF VALIDATION RESULTS.….…………………………….26

6.1 Approach ………………………………………………………………… 26
6.2 Role of EOSDIS ……….……………….……………………………… 26

6.3 Archival of Validation Data …………………………………………………. 27
6.4 Need for Additional Funding …………………………………………….. 27

7.0 SUMMARY ………….……………………………………………………….. 28

8.0 REFERENCES ……………………………………………………………….. 28

9.0 ACRONYMS ……...……..………………………………………………… 30

1.0 Introduction

1.1 Science Objectives

The Geoscience Laser Altimeter System (GLAS) is a multi-disciplinary earth science laser remote sensing instrument. An important objective of GLAS is the laser profiling (lidar) of atmospheric aerosols and clouds. The measurement science relates to the effect of cloud and aerosol on climate, primarily through the atmospheric and surface radiative balance. Knowledge of the height, coverage and thickness of cloud layers is essential in modeling the radiative fluxes at the surface and within the atmosphere. Clouds frequently occur in multi-layer systems on many spatial scales. Satellite based radiometers and imagers do an excellent job of viewing the cloud tops, but the presence of upper layer clouds limits their ability to distinguish multi-level cloud formations and to determine the vertical distribution of clouds. Passive remote sensors also tend to underestimate the fraction of optically thin clouds, while overestimating the percent of broken, optically thick clouds[1]. Recent sensitivity studies using calculations based on ISCCP (International Satellite Cloud Climatology Project) data indicate that the largest uncertainty in long wave radiative flux at the surface is caused by the lack of knowledge of the amount of cloud overlap or multi-layering[2]. Laser remote sensing, as will be done by GLAS, directly and accurately, measures the full three dimensional structure of clouds up to the limit of optical signal attenuation.

In addition to cloud effects, both natural and anthropogenic aerosol are also known to have important implications for the earth's radiative balance. Both direct (scattering and absorption of sunlight) and indirect (changing of cloud radiative properties) forcing by mainly sulfate aerosols has recently been shown to cause net regional cooling[3]. With current passive sensors, our ability to map the amount and extent of global aerosol is limited – especially over land. GLAS will significantly enhance our ability to observe the global distribution of atmospheric aerosol, both natural and anthropogenic. In particular the laser measurements will provide the only adequate measurement of the height distribution. The vertical distribution is particularly important for knowledge of aerosol transport. This has implications for improving climate models by providing better knowledge of the anthropogenic direct aerosol forcing, which at this point can only be estimated from sulfate source models. The detection of aerosol by GLAS is not dependent on the physical properties or composition of the aerosol itself, but the retrieval of aerosol extinction or optical depth is dependent on the aerosol optical properties which are in turn dependent on the physical and chemical composition of the aerosol.

The primary atmospheric science goal of the GLAS cloud and aerosol measurement is to directly observe the vertical structure and magnitude of cloud and aerosol parameters that are important for the radiative balance of the earth-atmosphere system, but which are ambiguous or impossible to obtain from existing or planned passive remote sensors. These parameters can be used to determine the radiative forcing and vertically resolved atmospheric heating rate due to clouds and aerosols. A further goal is to directly measure the height of atmospheric transition layers (inversions) which are important for dynamics and mixing, such as the planetary boundary layer (PBL).

1.2 Mission and Measurements

Scheduled for launch aboard ICESat (Ice, Cloud and land Elevation Satellite) in December of 2001, GLAS will be placed in a 600 km, near polar orbit (94° inclination) with repeat ground track of 0.5 year and a sub-cycle that nearly repeats in about a month. For a period of about 4 months immediately after launch, the spacecraft will be placed into an orbit with an eight day repeat cycle to support repeated overflights of verification sites. Also during this time the spacecraft will be in an orbit which maximizes the number of coincidences with EOS Terra and Aqua which will help in validating and calibrating various atmospheric data products. It is during this period that the most extensive validation efforts will be initiated. The atmospheric measurements will be obtained both day and night using two separate channels. The 532 nm, photon counting channel will be the most sensitive and will provide the highest quality data obtaining both aerosol and cloud returns. The 1064 nm channel will profile optically thick clouds and will be used mainly to supplement the 532 channel when and if it becomes saturated. The 40 Hz, solid state Nd:YAG laser will transmit short pulses of laser light that will produce a footprint 70 meters wide upon striking the surface, and each footprint will be about 175 meters apart. The backscattered light from atmospheric clouds, aerosols and molecules, will be digitized at 1.953 MHz, yielding a vertical resolution of 76.8 meters.

1.3 Validation Requirements

It is critically important to understand the accuracy and limitation of the GLAS atmospheric measurements. A comprehensive effort is planned to understand the accuracy of retrieved measurements and to verify the accuracy of the data products. The first aspect of the work is detailed development of the data retrieval algorithms and testing through aircraft observation based simulations. After launch there will be a program of comparison to ground based and airborne measurements to validate data products before release. A key part of the validation will be aircraft measurements by a new airborne lidar specifically designed for such research and comparisons with ground based lidar networks. Cooperative efforts to aid in the analysis and verification of GLAS measurements are will be pursued through contacts with outside lidar research groups.

Validation of measurements requires more than just airborne or ground based lidar measurements that are similar to the GLAS data. The basic altitude accuracy and signal linearity of the GLAS lidar measurement is in little question and will be simply checked with a few inter-comparisons to other lidar data. For higher level data products, it is most desirable to perform comparisons with measurements of proven quality that are obtained by much higher accuracy lidar or techniques very different from lidar. For cloud and aerosol detection and profiling, the major issue is the sensitivity of the measurement and the retrieval technique. The validation can be done from much higher signal strength ground and airborne lidar. A primary objective for the validation measurements is the need to obtain true simultaneity of data. The largest concern for good validation of the GLAS lidar data products rests with the optical cross section retrievals. Backscatter cross sections require a system calibration that may change with time. Derivation of optical extinction cross sections and layer optical thickness data products are very algorithm dependent and involve assumptions and corrections. Both the use of assumed integration variables in algorithm solutions and multiple scattering correction factors must be prominently mentioned as issues for retrieval of the optical thickness of transmissive cloud layers. Multiple scattering effects are not as large an issue for the retrieval of aerosol optical depths, but results are even more dependent on an unbiased assumption for the integration variables. Algorithm testing on data with known results is a requirement. After launch the field work and inter-comparisons must be extensive and ongoing. The algorithm development and tests and the planned validation activities are presented in the following sections of this document after a description of the GLAS data products in section 2.

2.0 Science Data Products

The GLAS raw data will be processed at the ICESat Science Computing Facility (SCF) located at Goddard Space Flight Center in Greenbelt, Md., using the ICESat Science Investigator-led Processing System (I-SIPS) which will produce the level 1 and 2 atmospheric and altimetry products within 4 hours of the receipt of all necessary input data. The level 1b and 2 atmospheric products are:

GLA07 – 532 nm Calibrated Attenuated backscatter profiles (-1 to 41 km) at 5 Hz and –1 to 10 km at 40 Hz. 1064 nm calibrated attenuated backscatter profiles for –1 to 21 km at 5 Hz and –1 to 10 km at 40 Hz.
GLA08 – Planetary Boundary Layer (PBL) height at 5 HZ and 4 seconds. Elevated aerosol layer heights (top and bottom) at 20 second resolution above 20 km and 4 second resolution below 20 km. Polar Stratospheric Cloud (PSC) heights at 20 second resolution.
GLA09 – Cloud layer height (top and bottom) below 22 km at 4 second, 1 second, and 5 Hz. Cloud heights at 40 Hz below 4 km altitude.
GLA10 – Attenuation corrected aerosol and cloud backscatter cross section and extinction cross section
GLA11 – Thin cloud and aerosol layer optical depth.

The data products are stored locally at the Goddard SCF facility as well as being sent to the National Snow and Ice Data Center Distributed Active Archive Center (DAAC) in Colorado for permanent archival. The I-SIPS is a robust, multilevel, data processing software system that runs on the Goddard SCF computers. The Scheduling and Data Management System (SDMS), which is the top most level of I-SIPS software, controls the flow of data and schedules the execution of the science algorithms. The science algorithms include the level 1a, waveform analysis, elevation, and the atmosphere subsystems. More detailed information on the I-SIPS can be found in Brenner et al[4]. The GLAS atmospheric data products represent a level of data processing that can be comfortably attained in an isolated, autonomous environment such as the I-SIPS. The creation of higher level products (level 3 and higher) and refinements to the level 2 data products is planned, but will likely require a certain level of interaction with the data as well as input from other data sources. These level 3 data products will be created on a case by case basis by the GLAS science team members. Further information on the data products and the algorithms used to produce them can be found in the GLAS Atmospheric Data Products Algorithm Theoretical Basis Document (Palm et al.[5]).

2.1 Expected Accuracy and Limitations

The various derived data products to be obtained from the GLAS atmospheric measurements are shown in Table 1. The horizontal and vertical resolutions will depend on the signal to noise ratio of the data which is a function of the atmospheric backscatter cross section and the amount of background light (reflected sunlight). The spatial resolutions shown are the typical resolutions expected, but will vary according to the signal to noise ratio of the data. In practice, if the signal to noise is too low to obtain a given measurement, data are averaged to increase the signal to noise ratio. The expected accuracy refers to the ability of making the measurement to within a given percentage of the actual value. For example, if the actual optical depth is 0.1, we expect to be able to measure it to within 50 % of that or 0.1 ± 0.05. The expected accuracy is also dependent on signal to noise of the data, and the values shown are for the expected average atmospheric conditions. Multiple scattering is a concern for some of the atmospheric measurements. For example, it will not affect the accuracy of cloud top height, but will at times be a problem with the location of cloud bottom. It will also affect the calculation of cloud optical depth, and much less often, aerosol optical depth. We plan to correct for the

Table 1. GLAS Level 2 Science Data Products.

Measurement	Spatial Horizontal	Resolution Vertical	Expected Accuracy	Range of Measurement
Cloud Optical Depth	10 km	___	50%	0.01 - 3.0
Cloud Scattering Cross Section	10 km	76 m	10%	10^{-6} - 10^{-1} (1/m-sr)
Aerosol Scattering Cross Section	30 km	76 m	10%	10^{-7} - 10^{-4} (1/m-sr)
Aerosol Optical Depth	30 km	___	50%	0.01 - 3.0
Cloud Top Height	200 m	76 m	100 m	300 m-22 km
Cloud Bottom Height	200 m	76 m	200 m	150 m-22 km
Tropospheric Aerosol Top and Bottom Height	30 km	76 m	150 m	400 m-38 km
PBL Height	2 km	76 m	150 m	150 m-6 km

multiple scattering affects on cloud optical depth using a Monte-Carlo model. The magnitude of multiple scattering is highly dependent on the particle size and shape. Because GLAS cannot retrieve information on particle properties, we will make assumptions based on geographic location, temperature, height and whether the scattering layer is cloud or aerosol. The multiple scattering correction factor will be obtained from a pre-calculated table made from many runs of the Monte Carlo model for varying cloud and aerosol properties.

2.1.1 Calibrated Atmospheric Backscatter

A major problem for any lidar system is the accurate determination of the instrument calibration constant. While this can be approximately calculated from laboratory measurements, it is much more accurate and reliable to calculate the system calibration constant on a continuous basis using the backscattered signal from clean (no aerosol or cloud) regions of the atmosphere. The backscattered power (P)received by the lidar is given by:

(1) $$P = \frac{CE\beta T^2}{R^2} + B$$

where P is the received power (Amps), E the laser energy, C the system calibration constant, β the total backscatter cross section (aerosol plus molecular), T^2 the two way path transmission, R the range from the spacecraft to the scattering volume, and B the background radiation intensity. The value of C depends on instrument component characteristics such as detector quantum efficiency, system optical efficiency and thermal stability. Because the calibration constant tends to drift with time, it is important to continuously calculate the system calibration during the entire lifetime of the instrument. There will certainly be a long time drift in C related to the degradation of laser energy, detectors and system optics, but also shorter time scale variations in C related to thermal changes and boresite drift will also occur.

Since the value of the molecular (Rayleigh) backscatter cross section is only a function of atmospheric density, if the temperature and pressure are known, then the molecular backscatter cross section can be accurately computed. Further, if a section of atmosphere can be identified as being cloud and aerosol free, then it can be assumed that the backscattered signal received by the lidar will be from molecular scattering only. With this assumption, and denoting z_c as the height of the cloud and aerosol free layer, C can be calculated as:

(2) $$C_\lambda = \overline{P'_\lambda(z_c)} / (\overline{\beta_m(z_c,\lambda)} T^2(\lambda))$$

where $\overline{P'_\lambda(z_c)}$ and $\overline{\beta_m(z_c,\lambda)}$ are the horizontal average (taken through a distance of about 1000 km along the GLAS orbit) of the received lidar signal and molecular backscatter, respectively, and $T^2(\lambda)$ is the two-way path atmospheric transmission from the top of the atmosphere to the height z_c. The largest error involved in the computation of (2) will usually come from uncertainty in β_m, which depends on temperature and pressure. At the altitudes where the 532 channel will be calibrated (30 km), it is estimated that temperature and pressure errors will be between 1 and 2 percent each. Taking the larger value means that the likely error in β_m will be about 3 percent. Applying standard error propagation analysis to Equation 2 yields:

(3) $$\left[\frac{\Delta C}{C}\right]^2 = \left[\frac{\overline{\Delta P(z_c)}}{\overline{P(z_c)}}\right]^2 + \left[\frac{\overline{\Delta \beta_m(z_c)}}{\overline{\beta_m(z_c)}}\right]^2 + \left[\frac{\Delta T^2(z_c)}{T^2(z_c)}\right]^2$$

Assuming reasonable uncertainties that should apply at the 30 km height for the 532 channel gives:

$\left[\frac{\Delta C}{C}\right]$	$\left[\frac{\overline{\Delta P(z_c)}}{\overline{P(z_c)}}\right]$	$\left[\frac{\overline{\Delta \beta_m(z_c)}}{\overline{\beta_m(z_c)}}\right]$	$\left[\frac{\Delta T^2(z_c)}{T^2(z_c)}\right]$
0.04	0.02	0.03	0.02

Thus, the typical error in the 532 channel calibration constant should be on the order of 4 percent. This will translate directly into a 4 percent error in the calibrated, attenuated backscatter cross section. The actual atmospheric backscatter cross section (corrected for attenuation) will have additional error associated with the computation of extinction.

2.1.2 Cloud and Aerosol Layer Heights

Aerosol and particularly cloud layer heights are the most straightforward of the GLAS retrievals. For aerosol layers, the accuracy depends on the signal to noise ratio of the data, which is a function of layer optical depth, background lighting conditions and the number of shots averaged. The same is true of clouds, but the effects of multiple scattering and signal attenuation become a concern for the accurate retrieval of cloud bottom. In addition, when the signal is sufficiently attenuated, cloud base cannot accurately be determined. Modeling results have indicated that cloud bottom retrieval will be limited to clouds of optical depth less than 3. The overall accuracy of cloud bottom will suffer after an optical depth of about 2 because of multiple scattering and signal attenuation.

In this case, the GLAS processing algorithms will set a flag to indicate that this condition has occurred. In addition, when multiple scattering is thought to be a problem (based on the magnitude of the integrated attenuated backscatter), a flag will be set that indicates a low confidence in the cloud base result. Based on simulation results for 4 second averaged data, we expect that the GLAS algorithms will be able to detect cloud and aerosol layers with optical depths as low as 0.005 to 0.01 during nighttime and between 0.05 and 0.10 during the day. The accuracy of the algorithm retrieval can be ascertained from the lidar data itself by overlaying the heights directly on an image of the backscatter data. An example, taken from the output of version 1 of the elevated aerosol layer (EAL) height algorithm, is shown in Figure 1. The layer top is shown as a white solid line, and the layer bottom is the black line. The exact same approach can be used for cloud top and bottom verification, but the effects mentioned above must be considered for cloud bottoms.

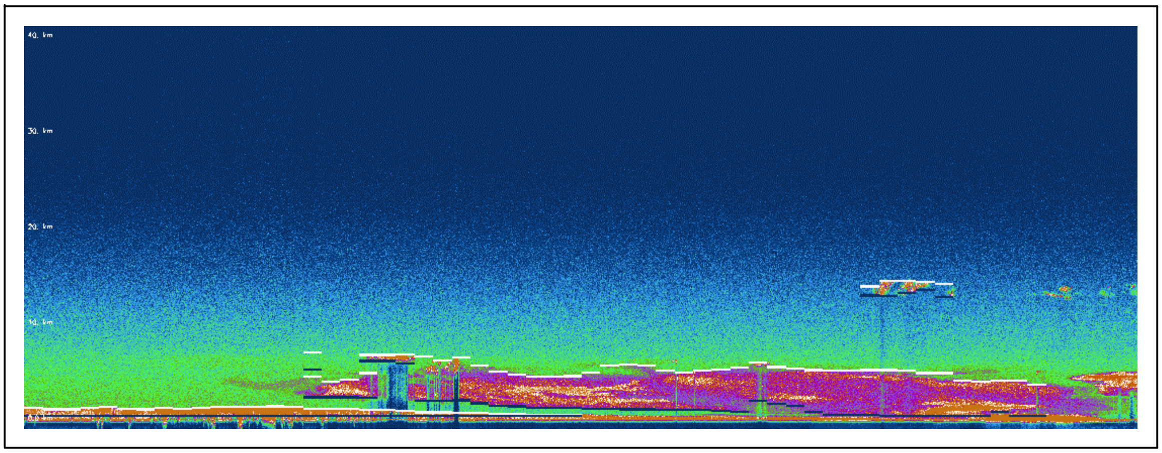

Figure 1. Output from a prototype EAL algorithm using LITE data as input. The aerosol layer is below about 5 km. The top and bottom of the aerosol layer, as resolved by the algorithm, is shown as the white and black lines superimposed on the image, respectively.

2.1.3 Cloud and Aerosol Layer Optical Depth

There will be maximum and minimum values for the retrieved optical depth. The minimum detectable optical depth is actually a function of the background intensity and how many shots are averaged. The GLAS optical depth retrieval algorithm will work with fixed time averaging intervals (4 and 1 second averaged data) and thus the minimum detectable optical depth will depend on the background only. Modeling studies have indicated that for a 1 km thick cloud or aerosol layer, the minimum detectable optical depth will be about 0.01 during night and between 0.05 and 0.10 for daytime. The GLAS retrievals will be limited to a total column optical depth of about 2. Values exceeding this will attenuate the signal to such a degree that it cannot be distinguished from noise.

The accuracy of the optical depth retrievals will depend on how well calibrated the data is and on the method which is used to obtain extinction from the attenuated backscatter cross section, which is what GLAS actually measures. Optimally, GLAS processing algorithms will use a procedure known as the signal loss technique, where the signal from a 'clean' layer below the cloud or aerosol layer is used to calculate the attenuation. Under these circumstances, the optical depth can be retrieved more accurately than the value stated in Table 1. For the cases where a clean layer does not exist below the particulate layer, an assumed extinction to backscatter ratio for particulates (S_p) will be used to obtain the extinction from the measured backscatter. Unfortunately, S_p varies considerably (10 – 100) for various cloud and aerosol types and thus introduces a large uncertainty into the optical depth calculation. The range of S_p can be narrowed down if one is able to classify the scattering layer in some way. For instance, if the layer can be identified as a cirrus cloud (based on height, temperature and scattering intensity) or desert dust (based on height, scattering intensity and geographic location), then the range of S_p (and the likely error) can be significantly reduced. An example of measured backscatter to extinction ratio ($1/S_p$) for mid latitude cirrus clouds (Eloranta et al.[6,7]) is shown in Figure 2. While the values of S_p

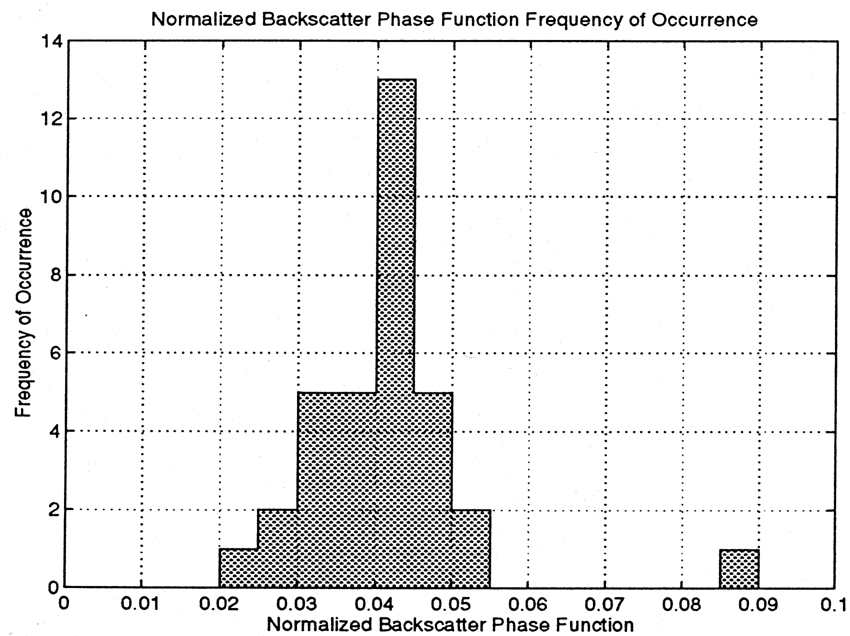

Figure 2. Backscatter to extinction ratio (*1/S*) for Midlatitude Cirrus Observations.

range from about 15 to 50, the distribution is narrowly peaked at about S_p=25. Similar approaches can be used for aerosol, if it can be reliably categorized. Such categorization would include desert dust, marine aerosols, sulfates and biomass burning, mainly by the height and geographic location of the layer. The sensitivity of the computed optical depth to errors in the assumed S_p ratio is a function of the optical depth of the layer. The error becomes greater as the optical thickness of the layer increases. To demonstrate this, we begin with the following definitions:

(4) $T_p'^2(z_b) = 1 - 2S_p'\gamma(z_b)$ (ignoring the molecular component),

(5) $\tau_p'(z_b) = -\frac{1}{2}\ln\left[T_p'^2(z_b)\right]$, and define the parameter

(6) $\alpha = S_p'\gamma(z_b)$, where $0 < \alpha < 0.5$ and $\gamma = \ P_n dz$

where the prime denotes the apparent values without the correction for multiple scattering, P_n is the calibrated, attenuated backscatter cross section, and z_b denotes the height of the bottom of the layer. Differentiation of 1 above, yields:

(7) $dT_p'^2 = -2\gamma dS_p' - 2S_p' d\gamma = -2\left(\alpha\frac{dS_p'}{S_p'} + d\alpha\right)$ and $d\tau_p' = -\frac{1}{2T_p'^2}dT_p'^2$

Substituting for $dT_p'^2$ and assuming $d\alpha$ is zero we have:

(8) $$d\tau_p' = \frac{\alpha}{(1-2\alpha)}\frac{dS_p'}{S_p'}$$

and noting that $\alpha = (1-e^{-2\tau})/2$, and substituting we get:

(9) $$\frac{d\tau_p'}{\tau_p'} = \frac{1-e^{-2\tau_p'}}{2\tau_p' e^{-2\tau_p'}}\frac{dS_p'}{S_p'}$$

We can use Equation 9 to obtain an estimate of the change in retrieved optical depth for a given uncertainty in S_p. We believe that typical errors in S_p will be about 25%. Figure 3 shows the error in estimating the optical depth as a function of true optical depth assuming $dS_p'/S_p' = 0.25$. It can be seen that the error in tau approaches the error in S_p as the true optical depth approaches 0. Thus, the error in retrieved optical depth for the

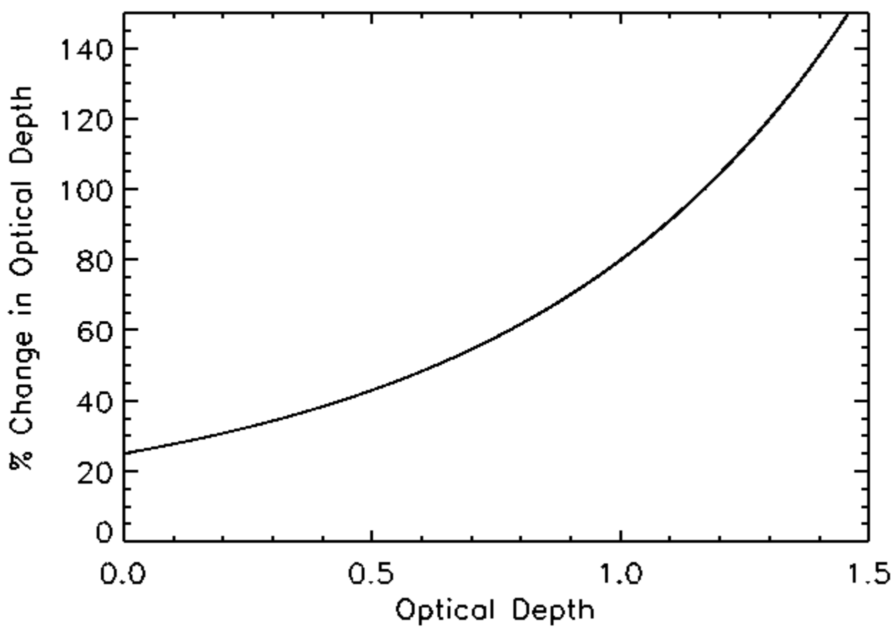

Figure 3. The error in retrieved effective optical depth when using an assumed extinction to backscatter ratio that is in error by 25 percent. The x axis represents the true effective optical depth of the layer.

GLAS measurements will depend directly on the error in S_p and for a given S_p error, will be greater for optically thick cloud and aerosol layers. Because uncertainties in S_p are unavoidable and often large, we will attempt to calculate S_p from the lidar data as much as possible using the signal loss technique mentioned above. Unfortunately, this will never be possible for the PBL, and will only be applicable to transmissive clouds and elevated aerosol layers.

A very major additional factor of the accuracy of lidar measurement of the optical thickness of transmissive clouds is the effect of multiple scattering. Multiple scattering, or more accurately forward scattering, will increase the strength of the lidar signal from below clouds over that if only single scattering were involved. Multiple scattering is particularly important for space borne lidar due to the large beam footprint. Calculations indicate that the increase in signal below clouds will typically be a factor of two to three. The optical thickness calculated directly from the signal will be in error from the true optical thickness by a similar factor. In order to correct for the multiple scattering, the multiple scattering is first modeled by radiative transfer calculation for an expected range of cloud types. As described in the GLAS ATBD a correction factor will be found from a table based on the cloud height, thickness and location. The correction will be an approximation.

Another source of error in the optical depth retrievals is signal noise which is unavoidable and considerably greater in the daytime than at night. We have tested the effects of signal noise on retrieved optical depth using simulated GLAS signals. The results indicate that noise induced error will not be nearly as great as that due to uncertainties in the extinction to backscatter ratio. Figure 4 shows a plot of the error as a function of noise to signal ratio. In general, the GLAS algorithms used to locate layer top and bottom will not function above a noise to signal ratio of about 0.5. Thus, noise induced error in the optical depth retrievals are expected to remain below 10 percent.

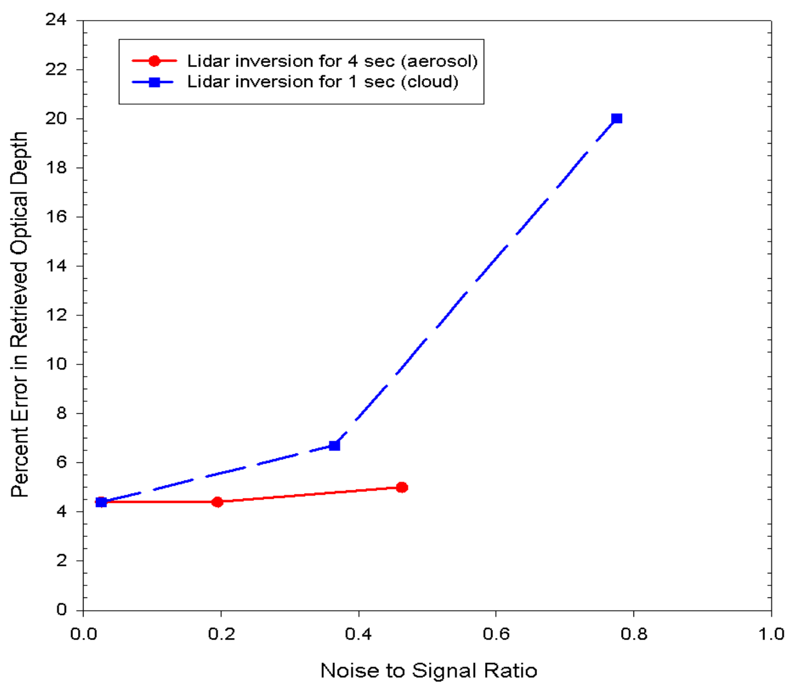

Figure 4. Accuracy of lidar inversion retrievals for layer optical depth as a function of signal noise using simulated GLAS backscatter profiles.

3.0 Validation Criterion

3.1 Overall Approach

3.1.1 Pre-Launch

The validation program will consist of pre-launch and post-launch activities aimed at establishing the accuracy of the GLAS algorithms for retrieval of atmospheric parameters. Prior to launch, simulated GLAS data sets will be produced using the GLAS Atmospheric Lidar Simulator (GALS) program which uses data acquired by the Cloud and Aerosol Lidar System[8-10] (CALS). We believe these simulations closely resemble the characteristics of actual GLAS data in terms of signal to noise and atmospheric variability. In addition to GALS, we have developed a second GLAS simulation program (Cloud and Aerosol Simulator (CAS)) that is based on a simulated, hypothetical atmosphere which is generated by the program using pre-defined input parameters of the cloud and aerosol layer characteristics. The first method has the advantage of being realistic by providing actual atmospheric variability while the second method has a distinct advantage when using the data to verify atmospheric retrieval algorithms, since all the answers are known (as they are inputs to the model). The GLAS data analysis algorithms will be developed and tested using the simulated GLAS data sets produced by these programs. The algorithm output will be validated in a number of ways. For certain GLAS atmospheric products (cloud top height, PBL height and aerosol layer height), validation is possible by assembling the GLAS backscatter data into color images which show backscatter strength as a function of height and along track distance. The output from the cloud top, PBL top or aerosol layer height algorithms are overlaid onto the color backscatter image (as in Figure 1). If the cloud heights have been correctly retrieved, they will line up with the clouds easily discernable on the backscatter image. The same is true for aerosol layers and PBL height. In addition, when the layer height algorithms are run on the output of the CAS program, the exact cloud and aerosol layer heights are known inputs to the CAS program and the algorithm output will be verified by comparing it to this input file. The validation of optical depth and extinction profiles during the algorithm development phase will be made by running the algorithms on simulated GLAS data produced by the Cloud and Aerosol Simulator (CAS) program. The GLAS calculated values of optical depth and extinction can be directly compared with the known values used by CAS.

We are also working on assembling a global network of Micro Pulse Lidar (MPL) systems (this is discussed further in Section 4.2.2) which would most likely be located at existing AERONET sites. After launch the AERONET data will be used to validate the GLAS retrieval of aerosol optical depth (total column). The co-located MPL data will be used to validate aerosol optical thickness, extinction profiles boundary layer height, and cloud and aerosol heights. In addition to the MPL-AERONET sites, we plan on placing 3 MPL lidars along an eight day repeat orbit track separated by about 100 – 200 km. This will enable better characterization of the atmosphere along the flight track and will provide a more representative sampling of the atmosphere for comparison with the GLAS data. In this effort, we hope to involve the education community by installing the MPL systems at a middle or high school and enlisting the help of the students with data gathering activities. This will most likely take place in Oklahoma, as discussed in section 4.2.2.

3.1.2 Post-Launch

A crucial validation activity that will occur after launch is the design and deployment of an aircraft field mission specifically designed to collect validation measurements along numerous GLAS ground tracks. This would entail flying the NASA ER-2 with at least the Cloud Physics Lidar (CPL) and the MODIS Airborne Simulator (MAS). A detailed description of this activity is given in section 5. Missions of opportunity will also be exploited where field experiments, not necessarily related to EOS, are using aircraft which can accommodate a lidar system. Piggy-backing in this way will give us more opportunities to acquire coincident data while keeping costs to a minimum. Post launch validation efforts will also rely on ground based lidar networks such as MPLNet and EARLINET throughout the lifetime of the GLAS mission. While the aircraft missions are invaluable, we realize they occur infrequently and that ground based measurements are extremely important. We also plan to involve the global ground based lidar community, giving them an opportunity to collect coincident data during times of GLAS overpasses.

3.2 Sampling Requirements and Tradeoffs

The major difficulty in obtaining validation measurements for the GLAS atmospheric products lies in the sampling coincidence requirements. The atmosphere has various length and time scales which determine how close in space and time a validation measurement must be to a GLAS observation in order for it to be useful. These scales depend on atmospheric state and the phenomena being measured, but are generally about 2 – 10 km and 10 – 30 minutes for the troposphere. For ground based validation measurements, this puts limits on both how close an overpass must come to the ground site, and how many GLAS profiles can be validated. GLAS travels at about 7 km/s and therefore will cover 10 km in about 1.4 seconds. Thus, a ground based measurement will be useful for validating no more than one and a half seconds of GLAS data. The ground based validation measurements will have to be carefully screened to eliminate cases where the atmosphere is highly variable (close to fronts), so that the horizontal averaging of the GLAS data (which may be required to obtain a given measurement) does not render it unrepresentative of the ground based point measurement. This could be accomplished using the ground based data itself by computing the variance of the atmospheric backscatter as a function of time. High variance situations would require a more stringent space/time coincidence in the two measurements while low atmospheric variance with time would indicate that the space/time coincidence criteria could be more relaxed.

The situation improves considerably if a fast moving aircraft is used to collect the validation measurements. The NASA ER-2 travels at about 200 m/s and can be flown directly underneath the GLAS track. In 20 minutes, the ER-2 can travel 240 km and can thus be used to validate over 30 seconds of GLAS data. The footprint size for the CPL is only about 1 meter, versus about 70 meters for GLAS. The major difficulty will be in aligning the ER-2 flight track with the GLAS overpass. With the high precision pointing ability of GLAS and the use of GPS positioning for the ER-2, aligning the ER-2 underneath the GLAS track should not be a problem.

3.3 Measures of Success

Validation experiments are conducted to evaluate the accuracy of the GLAS retrieved atmospheric parameters. The validation measurements themselves will of course have errors associated with them. A very important part of the validation process is correctly assessing the magnitude of the validation measurement error. We will assume agreement when the error bar of the validation measurement overlaps with the estimated error bar of the GLAS retrieval. For instance, to validate aerosol optical depth using a ground truth measurement obtained by sun photometer, the magnitude of the error associated with the sun photometer measurement must be known so that the accuracy of the GLAS measurement error can be evaluated.

Table 2. Expected Resolution and Accuracy for the new Cloud Physics Lidar System.

Measurement	Spatial Horizontal	Resolution Vertical	Range of Measurement	Expected Accuracy
Cloud Optical Depth	1 km	___	0.01 - 2.0	20%
Cloud Scattering Cross Section	1 km	30 m	10^{-6} - 10^{-1} (1/m-sr)	10%
Aerosol Scattering Cross Section	2 km	30 m	10^{-7} - 10^{-4} (1/m-sr)	10%
Aerosol Optical Depth	2 km	___	0.01 - 2.0	20%
Cloud Top Height	50 m	30 m	300 m-18 km	30 m
Cloud Bottom Height	50 m	60 m	200 m-18 km	60 m
Tropospheric Aerosol Top and Bottom Height	2 km	60 m	200m-18 km	60 m
PBL Height	500 m	60 m	150 m-6 km	60 m

The Cloud Physics Lidar (CPL) will undoubtedly be one of our prime validation tools. It has much better horizontal and vertical resolution than the GLAS measurements and should be able to retrieve extinction and optical depth more accurately as well. Table 2 lists tentative information on the spatial resolution and relative accuracy of the various atmospheric measurements made by the CPL. While the spatial resolutions are correct, the accuracy of the products has yet to be verified. An important factor for the CPL measurements is that the system field of view is sufficiently small that multiple scattering is not a significant factor. Therefore GLAS retrieval algorithms can be tested without the complication of an uncertain correction for multiple scattering. Similarly in GLAS underflights it is believed that the CPL cloud optical thickness will be a true independent measurement to compare with the GLAS data product.

4.0 Pre-launch Algorithm Test/Development Activities

4.1 Field Experiments and Studies

In most cases, algorithm validation will proceed hand-in-hand with the algorithm development cycle. Coding of the GLAS atmospheric channel algorithms requires the use of actual lidar data sets with which to test the algorithm as it is being developed. Ideally, the test data sets would come from a system that is similar to GLAS and would span large areas of the globe. Unfortunately, no such data sets exist. However, in 1994 the Lidar In-space Technology Experiment (LITE) was flown aboard the shuttle and acquired global lidar measurements from space for the first time. The lidar instrument flown in LITE is considerably different than GLAS, and in general the data quality is completely unsuitable for development and testing of GLAS data products. However the data set does exist and we think it is possible to use LITE data for testing of a very limited set of the GLAS data products, and indeed, such testing has already begun. In addition, we will test the algorithms using the GLAS simulated data sets generated by the GALS and CAS programs as described in section 3.1.

Since GALS uses actual lidar data acquired from prior field missions, and essentially adds noise to and degrades the data, the original aircraft lidar data can be used as input to an independent set of algorithms to retrieve a given GLAS atmospheric product. This retrieval, whether it be cloud top height, boundary layer height or optical depth, will be more accurate and much easier to retrieve than from the simulated GLAS data because of the much higher signal to noise ratio of the aircraft data. Additionally, during most of the aircraft missions, ancillary and in-situ data are available which can be used to verify and/or supplement the retrievals made from the aircraft lidar data sets. The retrievals made from the aircraft data sets as well as the in-situ observations (where available) will then be used to validate the retrievals made from the GLAS simulated data using the GLAS algorithms. It should be noted that the algorithms used to process the aircraft data to generate the validation data set will be similar to, but distinct from, the actual GLAS algorithms. There is an extensive CALS data base archived at Goddard Space Flight Center which can be used to generate numerous GLAS simulations for algorithm development and testing. Table 3 lists the more recent experiments in which CALS has flown on the ER-2 in conjunction with other instruments.

In addition to the CALS flights, the new CPL instrument completed its first field deployment in the Safari 2000 experiment in southern Africa. The field campaign involved close collaborative measurements with instrumented ground sites and in situ aircraft measurements. In the six week deployment extensive observation of thick haze layers were acquired in addition to clear air and cloud conditions. The experiment concluded in September 2000. The data will be used to test GLAS retrievals in the manner described elsewhere.

Table 3. Prior ER-2 field experiments using CALS.

Field Campaign	Year	Principle Sensors	Primary Purpose
FIRE	1991	CALS, MAS, CAR	Synoptic scale cirrus
ASTEX	1992	CALS, MAS, CAR, microphysics probes	Marine stratocumulus clouds over the ocean
TOGA-COARE	1993	CALS, MAS, microphysics probes	Tropical cirrus clouds and multi layer clouds over the ocean
CEPEX	1993	CALS, MAS	Tropical cirrus and radiation budget
MAST	1994	CALS, MAS, microphysics probes	Marine stratocumulus clouds over the ocean
ARESE	1995		
ARMCAS	1995	CALS, MAS, CAR, AVIRIS, microphysics probes	Arctic stratus clouds over sea ice; multi- layer clouds; surface bidirectional reflectance
SCAR-B	1995	CALS, MAS, CAR, AVIRIS, microphysics, aerosol properties, AERONET	Smoke, clouds and radiation from biomass burning
SUCCESS	1996	CALS, MAS, HIS, AERI	Mid-latitude cirrus clouds over continents
WINCE	1997	CALS, MAS, HIS,	Cloud detection and properties over snow and ice
FIRE III / ACE	1998	CALS, MAS, HIS,	Arctic stratus clouds over sea ice
WISC-T2000	2000	CALS, MAS, HIS,	Cirrus clouds over snow

4.2 Operational Surface Networks

4.2.1 AERONET

As mentioned in section 3.1, the validation of GLAS aerosol optical thickness retrievals will be largely done using the AERONET global network of sun photometers. This network is currently comprised of over 75 sites worldwide and has been in operation (though with fewer sites) since the early 90's[11]. In Figure 5, we have made a map of all the AERONET stations that lie within 50 km of the GLAS 8 day repeat orbit that will be used in the GLAS validation phase which lasts about 3 months. Of the 76 total AERONET sites, 38 of them lie within 50 km of the proposed GLAS 8 day repeat orbit. The ICESat spacecraft has the ability to routinely point off nadir such that it can hit targets as far as 50 km from the sub-satellite point. Thus, all ground sites shown in Figure

5 can be used for GLAS validation. In Table 4, we have listed the geographic coordinates of the 12 AERONET sites that are within 25 km of the expected GLAS 8 day repeat orbit. The last column of Table 4 gives the approximate distance from the AERONET location to the expected GLAS overpass. The off nadir pointing required to hit these sites is less than 2.5 degrees and will be easy to accomplish.

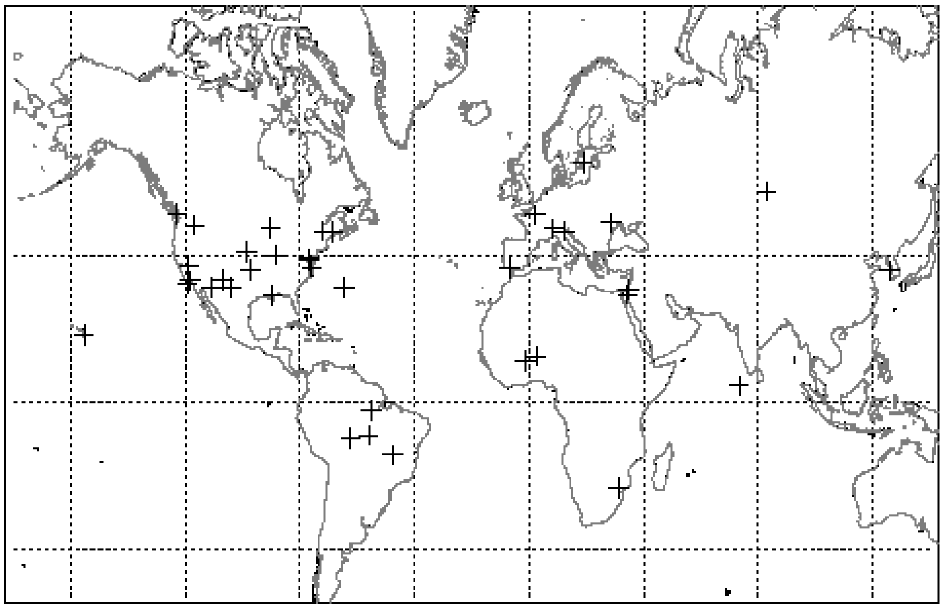

Figure 5. The locations of the 38 AERONET sites that lie within 50 km of the expected GLAS 8 day repeat orbit during the validation phase which occurs for a period of about 3 months after launch. As of this year, there are a total of 76 AERONET sites worldwide.

Table 4. The 12 AERONET sites that are within 25 km of the projected GLAS 8 day repeat ground track.

AERONET SITE	LATITUDE	LONGITUDE	DISTANCE(KM)
1	-10.70	-62.35	13.0
2	-15.50	-47.65	19.8
3	-9.91	-56.01	7.2
4	36.51	126.31	19.9
5	53.00	83.00	8.9
6	-2.63	-54.95	23.3
7	45.36	-71.91	16.1
8	37.10	-6.70	15.0
9	48.70	2.20	21.6
10	33.25	-119.40	11.9
11	30.51	34.47	24.3
12	30.36	-89.61	22.2

4.2.2 MPLNet

In addition to and complimentary with the AERONET sites, plans are underway for the establishment of a global MPL network (MPLNet) for use in EOS validation efforts including GLAS. Currently there are about 8 working MPL sites worldwide (Figure 6) and MPLNet will build upon this foundation to eventually double the number of MPL sites. The MPLs will be located at existing AERONET sites as the sunphotometer data is important for the analysis and interpretation of the MPL data. We hope to have MPL-net up and running by the middle of 2001. Data from other ground-based lidar sites around the world as well as sun photometer data from the AERONET global network of radiometers will be used as verification of aerosol optical thickness retrievals. The retrieval of boundary layer height and in some cases cloud layer height can be verified using data from the NWS radiosonde network. Preliminary results from current analysis of MPL data indicate that the MPL, when used in conjunction with sun photometer data, can retrieve aerosol layer optical depth with an accuracy of about 20 percent.

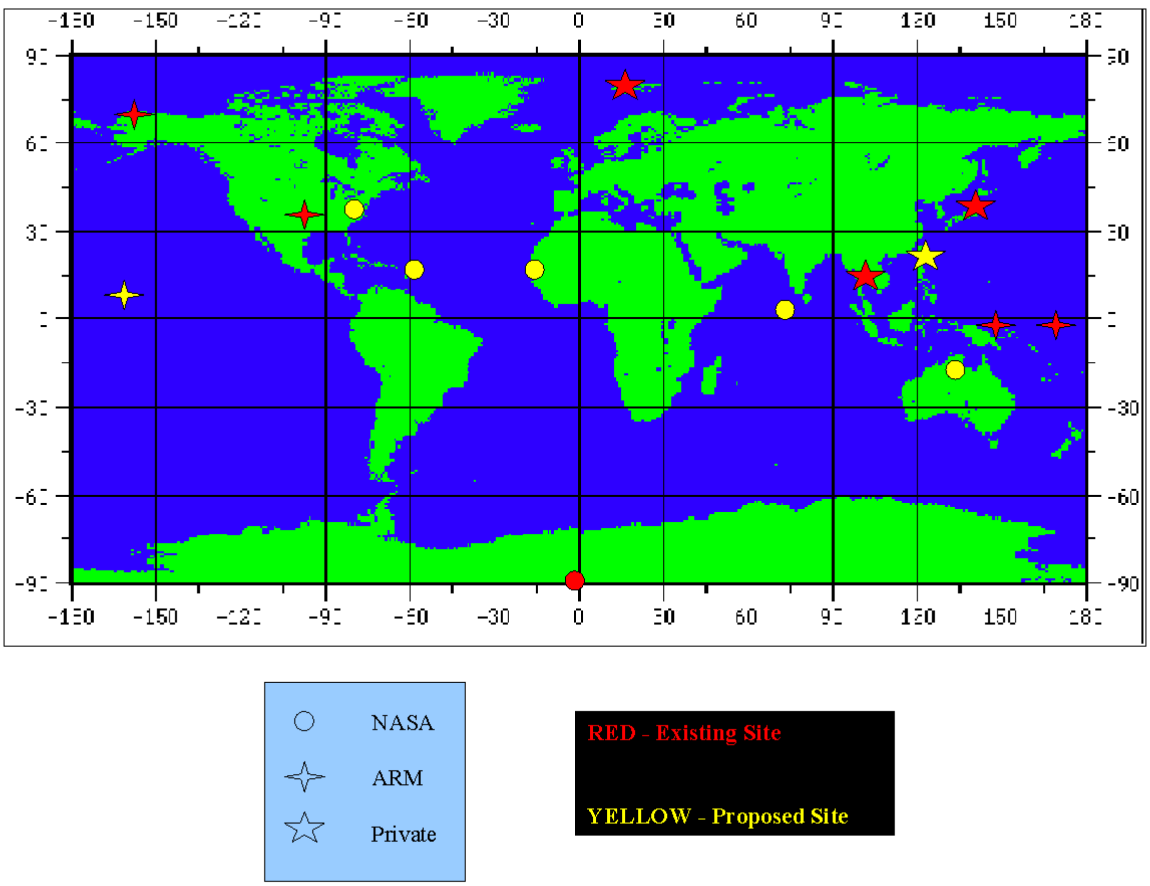

Figure 6. A map of the locations of existing and proposed MPL sites.

Table 5. The locations of the 9 MPL sites scheduled to be operating by the end of 2001 and the distance between them and the closest approach of the GLAS 8 day repeat orbit.

MPL SITE	LATITUDE, LONGITUDE	GLAS CLOSEST POINT	DISTANCE (KM)
South Pole	-90.00, 0.00	-86.02, -6.20	437
Greenbelt, MD	39.02, -76.87	39.19, -77.25	38
ARM, Manus	-2.07, 147.42	-2.26, 147.66	35
ARM, Naru	-0.50, 166.92	-0.23, 167.65	86
Barrow, Alaska	71.30, -156.68	71.42, -155.94	29
ARM Oklahoma	36.62, -97.50	36.87, -97.66	31
Barbados	13.18, -59.43	13.00, -58.97	53
Saudi Arabia	24.91, 46.41	25.11, 46.08	40
Jabiru, Australia	-15.00, 130.00	-15.16, 130.38	45

4.2.3 EARLINET

Another valuable source of ground based validation data can be obtained from the European Aerosol Research Lidar Network (EARLINET). Consisting of 21 ground based stations distributed over most of Europe, the goal of EARLINET is to establish a quantitative and comprehensive data base of both the horizontal and vertical distribution of aerosols on a continental scale. A further goal of EARLINET is to provide ground truth support for present and future satellite missions dedicated to the retrieval of global aerosol distribution. Thus, the use of EARLINET data for the validation of GLAS

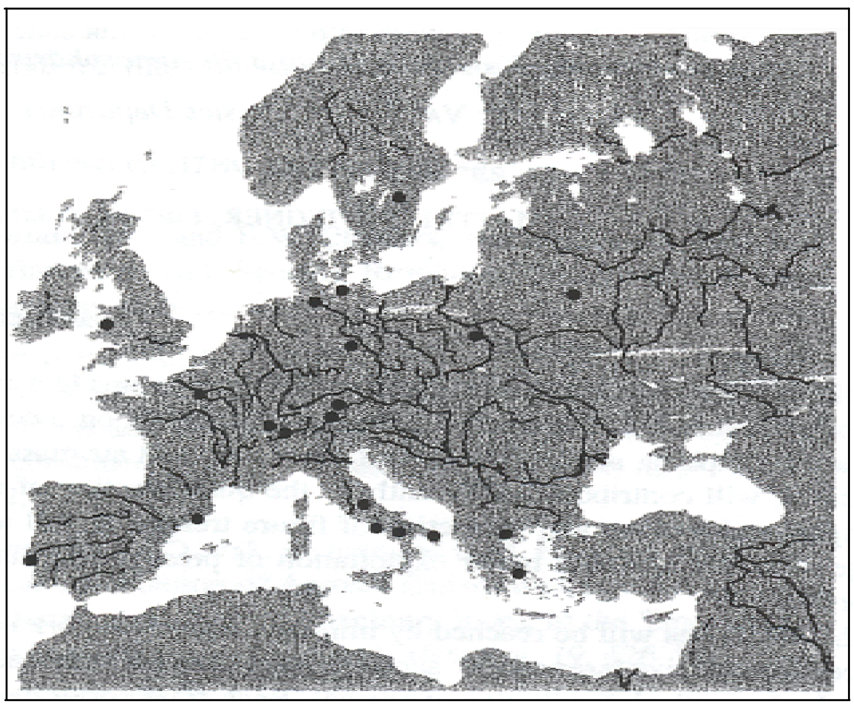

Figure 7. Network of EARLINET ground stations.

retrievals is in accordance with the goals established for the network. The ground based lidars are comprised mostly of RAMAN systems, capable of determining the extinction profile separately from the backscatter profile. Thus, EARLINET can provide validation for GLAS extinction profiles and optical depth retrievals as well as providing information on extinction to backscatter ratios. It is yet to be determined how many of the EARLINET stations are close enough (within 50 km) to the GLAS 8 day repeat overpasses to be useful, but we expect to use these sites for validation throughout the lifetime of the GLAS mission.

4.2.4 Asian Dust Observing Network

A network of ground based lidar systems has been operating since 1997 to monitor the seasonal outbreaks of dust which originate from vast desserts in China and Mongolia. The dust is blown up by strong wind behind cyclone passages and is transported in the free troposphere by the westerly jet. The dust outbreaks are most frequent in the springtime and can cover large areas. It is not uncommon for the dust to extend across the Pacific Ocean and at times reach North America. Most of these sites include sun photometer measurements as well. We intend to use the observations from a number of these stations to compare cloud and aerosol layer height and optical depth retrievals.

Figure 8. Asian Dust observation network

4.3 Existing Satellite Data

During the pre-launch algorithm development phase, satellite data is generally not required for validation activities that can be performed at this time.

5.0 Post-launch Activities

5.1 Planned Field Activities and Studies

The products from the GLAS atmospheric channel algorithms will be tested, verified, and validated to the fullest extent possible using available ground based radiation and cloud networks, EOS targeted field validation campaigns, and flights of opportunity which may occur during the lifetime of GLAS (3-5 years). The ground networks cover five main categories:

1) <u>Atmospheric Radiation Measurement (ARM) Sites from DOE:</u>
There are expected to be five sites around the world with micro pulse lidar (MPL) aerosol and cloud profilometers, MFRSR shadowband radiometers, and BBSS balloon sonde atmospheric sounders, all capable of long-term assessments of GLAS derived products. ARM site instrumentation will be involved in intercomparisons of cloud location (especially cloud bottom), attenuated backscatter cross section, aerosol extinction cross section, and optical thickness.

2) <u>Aeronet Radiometer Sites from EOS:</u>
Long term measurements from 78 sites around the world are providing optical ground based aerosol monitoring using automatic sun-sky scanning spectral radiometers. Some of the AERONET sites will be equipped with MPL's to measure vertical distributions of aerosol backscatter and extinction cross sections. The sunphotometer data will provide total column optical depth measurements. This will provide aerosol optical depth validation and possibly thin cloud optical depth validation as well.

3) <u>MPLnet Lidar Sites from EOS:</u>
As part of the general EOS validation scheme, 12 MPL's are now being shipped to various sites around the world to add to the aerosol and cloud database of the EOS ground validation network. They will be used for intercomparisons with GLAS products such as cloud location, aerosol and cloud backscatter cross sections, and optical thickness. The MPL-net locations are shown on the map of Figure 6 in Section 4.2.

4) <u>GLAS MPL sites:</u>
As discussed in 3.1, we plan to deploy 2 additional MPL's along the GLAS orbit track north and south of the existing MPL (ARM) site in Oklahoma. In addition, an MPL site has recently been established at the South Pole and we are examining the possibility of deploying one or two in Greenland as part of the GLAS validation program. These lidar systems will give extra cloud height and boundary layer height validation in climatic zones where ground monitoring is very sparse. If sun photometer data is also available, optical properties will be validated.

5) Ground based lidar community

There are many ground based lidar systems in operation at universities and research institutes around the world. We plan to develop a GLAS correlative measurements group consisting of 10 to 20 lidar sites around the globe. Examples of these include the HSRL[12] at the University of Wisconsin and the lidars at the University of Utah's Facility for Atmospheric Remote Sensing (FARS). Many of the ground based lidar sites will be part of the EARLINET and Asian dust monitoring networks as described in section 4.2. We will keep updated tables posted on the world-wide-web which indicate when an overpass of GLAS will occur for each site. The lidar data collected during the overpass would then be analyzed for parameters such as cloud top and bottom, backscatter cross section, and cloud and aerosol optical depth. Ideally the analysis will take place at the foreign site, with the results being sent to the GLAS atmospheric science team at Goddard, where they will be archived. The measurements obtained by these groups will themselves have to be verified for accuracy to as great an extent as possible. Generally, this verification is most important for thin cloud and aerosol optical depth, and less important for layer heights. Other instruments (sun photometers for instance) and satellite observations (MODIS, MISR) should be used whenever possible for this purpose. The main burden of this effort would be placed on the institution acquiring the validation data.

After an initial checkout phase lasting about a month, an intense inter-comparison (validation) period is scheduled during the next three months after launch. The ICESat orbit will be configured to enable an increase in overflights over targeted ground networks. Methodologies already developed by NASA/GSFC to generate cloud and aerosol products from MPL systems and AERONET radiometers will be directly adaptable when comparing to the GLAS products. Less intense inter-comparisons will be done after this period when the satellite will be in its normal orbit configuration. These will continue throughout the life of GLAS. We hope to take advantage of planned ER-2 field missions during this time (some of which are listed in Table 6), where one or more flights can be dedicated to flying under the GLAS ground track. The performance of the GLAS algorithms will be statistically evaluated and their accuracy within the different cloud and aerosol types will be classified. The goal of the inter-comparison during the dedicated evaluation period will be to certify the GLAS algorithm accuracy to within a known range of tolerance.

The products produced by the GLAS atmospheric channel algorithms will be extensively tested, verified, and validated by means of aircraft observations after the satellite has been launched into orbit. Since the algorithms were based upon many years of aircraft lidar remote sensing experiments, airborne validation procedures are evidently very appropriate for testing their efficacy and accuracy. Aircraft observations will be made at locations which are inaccessible to ground observations. Aircraft observations can be taken from a large geographical area in a short time compared to ground based observations. The NASA ER-2 aircraft has served as a platform for an atmospheric lidar during many experiments. It remains the best aircraft for this purpose because of its altitude, range, flight stability, and instrumentation capabilities.

5.2 New EOS-targeted Field Campaign

To validate the GLAS atmospheric measurements listed in Table 1 will require the use of the Cloud Physics Lidar (CPL) system together with the MODIS Airborne Simulator (MAS) onboard the NASA ER-2 aircraft. Data from the CPL alone will be sufficient to validate cloud and aerosol height, scattering cross section and PBL height. Data from CPL and MAS will be utilized to obtain aerosol and thin cloud optical depth using techniques developed over the years for use with CALS data. It is our understanding that a dropsonde system is under development for the ER-2 aircraft. Measurement of the temperature and pressure structure below the ER-2 will enable us to calibrate the CPL very accurately and to obtain precise measurements of the attenuated backscatter cross section. This will greatly aid our ability to vaidate the GLAS GLA07 data product.

We plan to perform a total of six validation flights, each about 4-6 hours in length. The flights will originate from Dryden Research Center in California. Basing the ER-2 at Dryden Research Center will minimize costs, yet enable the ER-2 to sample a wide area from the mid-west to the eastern Pacific Ocean, encompassing a wide variety of atmospheric conditions. After flying from Dryden to the selected GLAS orbit track, the ER-2 will fly underneath the GLAS orbit for about 1-2 hours. The exact track and location of the GLAS laser footprints can be calculated to a high degree of precision (within 100 m) well ahead of time. The ER-2 will then use GPS positioning to fly directly along the GLAS ground track. The flight will be timed such that GLAS will overfly the ER-2 at the midpoint of the time spent on orbit. The ER-2 then returns to Dryden. The total time of the flights will vary, but should be generally less than 6 hours.

A comprehensive ground-based validation effort will take place in White Sands, New Mexico during the 3 month validation phase. Every eight days the GLAS orbit will pass over White Sands. Much of the effort at White Sands will be geared toward the validation of the pointing accuracy of GLAS and the range measurements derived from the altimeter channel. However, current plans also call for the operation of a ground-based Micro Pulse Lidar (MPL) and sun photometer at White Sands and possibly another location along the orbit track that passes through White Sands. In addition, as we outlined in Section 3.2, three MPL's will be located along an 8 day GLAS repeat orbit track in Oklahoma, centered on the ARM CART site as shown in Figure 9. We would probably fly the White Sands and Oklahoma orbit tracks twice during the validation period. In addition to these four ER-2 flights, we would make another 3 or 4 flights of GLAS orbits that are within 1500 km or so of Dryden. Of these, one should be chosen which comes close to the Los Angeles metropolitan area (to obtain data that would include anthropogenic aerosol) and another off the coast of California (marine boundary layer and stratus). The other flights would be determined mainly by the weather, as there is a particular interest in the retrieval of thin cloud (cirrus) height and optical depth. At least one of the flights should occur at night, so that we may assess the impact of background light on the GLAS atmospheric retrievals.

The total time required to execute the 7 ER-2 flights will be on the order of 2-3 weeks. We anticipate roughly 35 hours of ER-2 flight time (including ferry time) will be required to accomplish the validation objectives. Assuming a mid December, 2001 launch date, the two weeks required for the mission would occur sometime between late March and early June, 2002. The CPL data will be analyzed in the field at Dryden for cloud and aerosol height, while the optical depth retrievals will be done later at Goddard using the combined analyses of both the CPL and MAS data. These results will then be compared with those obtained from the ISIPS software for the co-aligned data obtained by GLAS.

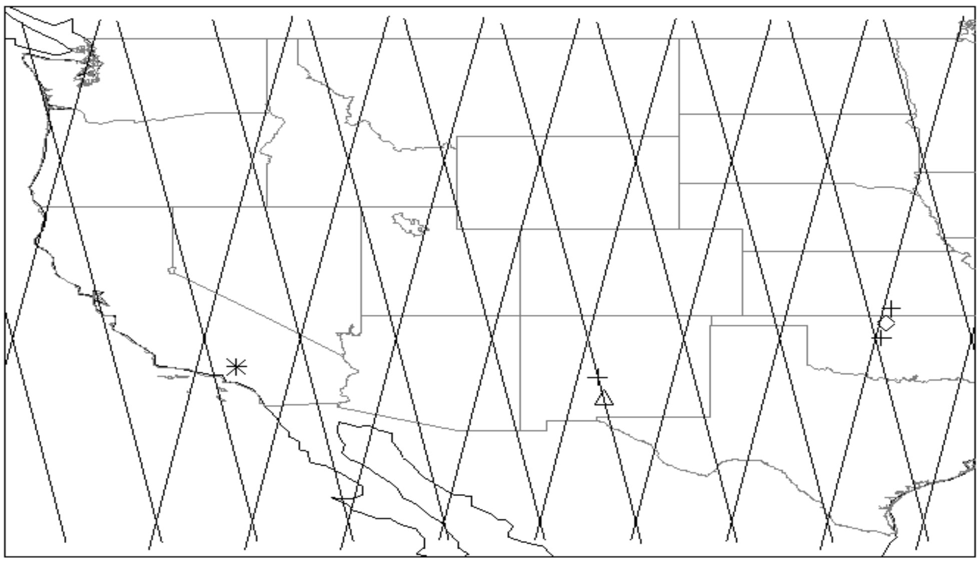

Figure 9. A map of the central and western US with the 8-day repeat GLAS orbit tracks and the locations of Dryden Research Center (*), White Sands, New Mexico (Δ), and the ARM CART site in Oklahoma (◊). Also shown are the proposed locations of MPL sites (+) for use during the 3 month validation phase.

An alternative scenario for the ER-2 field mission during the validation phase would be to deploy the aircraft to Fairbanks, Alaska. A mission flown out of Fairbanks would have the advantage of being able to fly 3 or 4 consecutive GLAS overpasses in a single day. This is possible because at the latitude of Fairbanks, the spacing of consecutive GLAS tracks is roughly 500 km, whereas over the central US, the track spacing is close to 1200 km. The ER-2 can fly about 500-600 km/hr and there is about 90 minutes between GLAS overpasses. Thus, over Alaska, the ER-2 could spend about ½ hour on a GLAS ground track, then spend an hour flying to the next GLAS track under which it would fly for another ½ hour, etc. Flying 3 such GLAS underflights would take about 4.5 hours, and with an estimated 3 hour return trip to Fairbanks, would entail a 7.5 hour total mission time. If this is repeated on 3 days, we would have acquired 9 coincident measurements for validation while expending a total of 22.5 flight hours. The mission described above flying out of Dryden would use about 35 flight hours, span 2 to 3 weeks, and yield only 6 coincident validation measurements. While the cost to deploy the ER-2 out of Fairbanks is considerable, it may be largely offset by the reduced number of flight hours.

When the GLAS spacecraft assumes its nominal orbit (after the initial 3 month validation period), the performance of the GLAS algorithms will be reevaluated with ER-2 and other aircraft flights on an episodic basis. This will be done when a situation of opportunity arises for GLAS underflights during the many atmospheric aircraft experiments which typically take place within the planned lifetime of GLAS. During such experiments, it will often be possible to design one or more aircraft sorties to serve as a GLAS underflight. Depending upon the specific instrumentation of a given flight, the products of one or more of the GLAS algorithms will be evaluated. The performance of the instrument will be evaluated for degradation. Such degradation may require that the algorithms be modified. Also, the performance of the algorithms in additional categories of cloud situations will be analyzed and these results added to the performance catalog. A tentative list of future aircraft experiments which might serve as GLAS validation opportunities is presented in Table 6.

The combination of dedicated aircraft lidar underflights immediately after the launch of GLAS and the episodic flights during its lifetime will give investigators a high degree of confidence in the reliability of its products when they are incorporated into atmospheric studies.

Table 6. Future post launch (Dec 2001) field campaigns that may provide opportunities to collect GLAS validation data.

Field Campaign	Date	Principle Sensors	Location	Primary Purpose
LBA E-3	1-Apr-02	AVIRIS, MAS, AirMISR	Brazil	
Mini-CRYSTAL	1-Jun-02	ACLS, MAS, CARS, CPL	Florida	Tropical Cirrus Radiative Properties
LBA E-2	7-Apr-03	AVIRIS, MAS, AirMISR	Brazil	
CRYSTAL	21-Jun-04	ACLS, MAS, CARS, CPL	Guam	Tropical Cirrus Radiative Properties
CAMEX V	1-Aug-04	LASE	Florida	Hurricane Dynamics
CloudSat/ Picasso-CENA	15-Aug-04		West Pacific	Validation

5.3 Need for other satellite data

The validation of GLAS atmospheric parameters does not require the use of coincident satellite measurements, but when such coincidences occur, we plan to take advantage of them. Of the GLAS products shown in Table 1, satellite data is useful only for validating cloud and aerosol optical depth. The Terra and Aqua EOS platforms as well as AVHRR can be used for this purpose. Additionally, the multispectral infrared radiometer data from any of these satellites can be used to increase the accuracy of the GLAS retrieved optical depth. For the other GLAS data products, satellite retrievals are either unavailable (as in aerosol layer or boundary layer height) or are not accurate enough (cloud height retrievals) to be of use. We expect that PICASSO-CENA and CloudSat data will be used for validation and comparison when they become available, which most likely will not be until mid to late 2004.

5.4 Measurement needs at calibration/validation sites

Intercomparison measurements at the validation sites rely heavily on ground and airborne lidar, sun-photometers and radiosonde. During the 3 month validation period a few months after launch we plan to organize a field campaign using the ER-2, portable lidars (MPL), sun-photometers and GPS receivers. Ideally, 3 or 4 MPL's and sun-photometers would be deployed at separate sites along the GLAS ground track separated by 50 to 100 km. The GPS receivers would give us precise knowledge of the validation measurement location. The ER-2 would carry CPL, MAS, a visible imager and possibly another lidar. A second plane might also be used to acquire vertical profiles of extinction using sunphotometers. This would be extremely valuable to validate GLAS computed extinction profiles. Funding for aerosol sampling aircraft for support of the MODIS/MISR validation has been provided by the EOS program in the past and similar funding may be available for GLAS. The most difficult aspect of this plan is in finding suitable places for the ground based MPL systems, since they must lie exactly along the GLAS flight track. Possible sites are being investigated.

5.5 Need for instrument development

A major replacement to the ER-2 Cloud and Aerosol Lidar System (CALS) has taken place over the last year. The Cloud Physics Lidar (CPL) was used in its first field campaign during the SAFARI experiment in South Africa in August and September, 2000. The CPL includes the addition of a third channel (355 nm), multiple fields of view, and the use of photon counting detectors. The new design will allow the direct computation of thin cloud and aerosol optical depth, rendering it a more useful instrument for the validation of the GLAS atmospheric products. Currently, the CPL does not have the multiple field of view channels implemented, but continued work over the next fiscal year (2001) will enable the use of these channels by the time GLAS is launched. The CPL performed very well during the SAFARI experiment, and the large data set collected during SAFARI will provide valuable data for the testing of GLAS algorithms. We will also provide manpower for the assembly and alignment of a number of MPL systems which will become part of MPLNet as shown in Figure 6.

5.6 Geometric registration sites

There is no need for geometric registration sites.

5.7 Intercomparisons

The validation measurements will first be subjected to an error analysis to quantify the measurement accuracy. Only those measurements which were taken within a certain distance and time (as discussed in section 3.2) will be used. The comparison of cloud top height will be done using the ER-2 CPL data from the underflights when available. In other areas, ground based lidar and radiosonde data will be used. Cloud bottom will be validated from MPLNet, EARLINET and other ground based lidar sites. Aerosol and thin cloud optical depth derived from the GLAS data will be compared with sunphotometer data, Raman lidar and data from the University of Wisconsin's High Spectral Resolution Lidar[12] (HSRL) ground based lidar system. Satellite data from Terra, Aqua and AVHRR will be used when possible for validation of aerosol optical depth.

6.0 Implementation of validation results in data production

6.1 Approach

During the first few months after launch, before field validation measurements have been compiled, we will monitor the performance of the cloud top height, aerosol layer height and PBL height algorithms by simply overlaying the results on height-distance images of lidar backscatter as discussed in section 3.1. Adjustments to the algorithms can be made quickly based on these visual inspections. After field validation measurements have been acquired, detailed comparisons between the output of the GLAS processing algorithms and the validation measurements will be performed here at Goddard Space Flight Center by the GLAS atmospheric algorithm development team. Problems and deficiencies in algorithm performance will be identified and corrected. The improved algorithms will be tested on the GLAS data and compared with the results from as many correlative measurement sites as possible to insure their increased accuracy. After an initial, intensive validation period lasting 3 to 4 months, the processing algorithms will be replaced with improved versions, and all of the GLAS data acquired to that point will be re-processed. About six months to one year later, additional improvements to the algorithms will require a second re-processing of the data, based on a continuing assessment of algorithm performance using the ground based validation sites and aircraft data from missions of opportunity. We view validation as an activity that is to be carried out throughout the lifetime of the mission and plan on using data from mainly the ground based sites whenever possible for this purpose.

6.2 Role of EOSDIS

The data sent down from GLAS will be analyzed at Goddard Space Flight Center at the GLAS Science Computing Facility (SCF) apart from EOSDIS. Level 1 and 2 data products will then be generated at the SCF and sent to EOSDIS for archival and dissemination to the science community. EOSDIS will also be utilized to locate data sets from other satellites such as Terra, AVHRR, etc., that may be useful in validating the GLAS data products. An example of this would be the use of EOSDIS search tools to locate the occurrences of Terra data that are coincident with GLAS data.

6.3 Plans for archival of validation data

The validation data acquired by the correlative measurements program will be archived at Goddard by the GLAS atmospheric measurements principle investigator's (Dr. Spinhirne) group. This will consist of all data acquired during the EOS dedicated field mission and missions of opportunity (involving aircraft), the data from the MPL-net and AERONET, and possibly coincident data from Terra and or Aqua. Additional data obtained from other ground-based lidar sites will also be archived. We have a dedicated computer system (provided by GLAS funds) that has ample disk storage (up to about a terrabyte) and additional DLT tape storage. The data will be archived here and made available through anonymous ftp or a WEB page type interface. Such a data archive may prove very valuable to other EOS investigators, and we are committed to establishing an easily accessible and well documented validation data archive. These data will also be archived at the National Ice and Snow Data Center (NSIDC) in Colorado, which is one of the EOS Distributed Active Archive Centers (DAAC).

6.4 Need for Additional Funding

The science validation effort for any spacecraft mission is a costly, but crucial endeavor. Without comprehensive and accurate validation measurements, the science products produced by the processing algorithms have no real value. Thus, it is imperative to design a robust and well thought out validation plan. Of course, the execution of such a plan requires adequate resources. The cost of organizing one EOS dedicated field mission involving the NASA ER-2 aircraft during the 3 month validation phase has been included in our GLAS budget. The funding for this mission is adequate for only one aircraft. Ideally, we would like additional funds to involve a second aircraft for the in-situ measurement of aerosol properties and extinction profiles. This would greatly facilitate the validation of the GLAS retrieved extinction profiles. A separate proposal to establish and maintain the MPL-net lidar sites has been submitted to EOS management and has been favorably received. Assuming this is fully funded, the only other area which we would ask for additional funding help would be for establishing the additional MPL sites (as shown in Figure 6) that will be used during the 3 month validation phase. At present, these would have to be borrowed from existing MPL sites. A more desirable scenario would be to use funds to assemble 2 or 3 new MPLs here at Goddard, and use them not only during the 3 month validation phase, but throughout the lifetime of GLAS.

7.0 Summary

We have developed a validation plan which strives to insure the best quality retrievals for all of the GLAS atmospheric data products. Prior to launch we will be using mainly simulated GLAS data based on data gathered by the ER-2 CALS system during the last decade for algorithm development and testing. Development of a next generation lidar (CPL) is underway and will provide data sets that can be used for algorithm testing starting in late fall of 2000. Following launch, the validation efforts center on one or more EOS targeted field campaigns utilizing ground based (MPL) and airborne (CPL on the ER-2) lidar and sunphotometer (AERONET) measurements taken along the flight track of GLAS. Validation data gathered from selected ground based lidar sites around the world will also be used, but the usefulness of these data are limited compared to that obtained with aircraft. Care must be exercised to insure that the correlative measurements are co-located in space and time to within certain thresholds that depend on the local atmospheric variability. Table 7 lists, for each atmospheric product, the main correlative measurement that will be used to validate that product. Validation is an extremely important component of the GLAS science mission and careful planning must be done to insure its success.

Table 7. Validation Summary

GLAS Science Product	Validation Measurement	Validation Issues
Cloud optical depth	CPL, HSRL, MPL and AERONET	Multiple scattering correction, S ratio knowledge
Cloud scattering cross section	CPL, HSRL	Multiple scattering correction, S ratio knowledge
Aerosol optical depth	AERONET and MPL, Raman lidar, HSRL lidar, MODIS, AVHRR	S ratio knowledge
Aerosol scattering cross section	CPL, MPL	S ratio knowledge
Cloud top height	CPL, Radiosonde	Optical depths > .05
Cloud bottom height	MPL. Radiosonde	Multiple scattering; Optical depths < 2.5
PBL height	CPL, Radiosonde.	Multiple embedded layers; Optical depths > .05

8.0 References

1. Wielicki, B. A. and L. Parker, 1992: On the determination of cloud cover by satellite sensors: The effects of sensor spatial resolution. *J Geophys. Res*. **97**, 12, 799-823.

2. Wielicki, B. A., B. Barkstrom, E. Harrison, R. Lee, G. Smith, and J. Cooper, 1996: Clouds and the Earth's radiant energy system (CERES): An Earth observing system experiment. *Bull. Amer. Meteor. Soc.*, **77**

3. IPCC, 1995: *Climate Change* 1994. Cambridge U. Press.

4. Brenner, A., G. Marcus, J. Lee, P. Jester, S. Bhardwaj, and K. Barbieri, GLAS I-SIPS Software Detailed Design Document. Available online at: http://glas.wff.nasa.gov/docs/docs.html

5. Palm, S.P., W.D. Hart, D. Hlavka, E.J. Welton and J.D. Spinhirne, 2000: The Geoscience Laser Altimeter System (GLAS) Algorithm Theoretical Basis Document. GLAS Atmospheric Data Products. Available online at: http://www.csr.utexas.edu/glas/atbd.html

6. Eloranta, E. W., R. E. Kuehn and R. E. Holz, "Cirrus Cloud Backscatter Phase Functions Measured with the University of Wisconsin High Spectral Resolution Lidar" 10th Conference on Atmospheric Radiation, preprint, AMS, Madison, Wisconsin, 28 June–2 July, 1999.

7. Eloranta, E.W. and P. Piironen, 1996: Measurements of cirrus cloud optical properties with the University of Wisconsin high spectral resolution lidar , Advances in Atmospheric Remote Sensing with lidar, edited A. Ansmann, R. Neuber, R. Rairoux and U. Wandinger, Spinger-Verlag, New York, Berlin, Heidelberg.

8. Spinhirne, J. D., R. Boers and W. D. Hart, 1989: Cloud Top Liquid Water from lidar Observations of Marine Stratocumulus. *J. Appl. Meteor*., **28**, 81-90.

9. Spinhirne, J. D. and W. D. Hart, 1990: Cirrus structure and radiative parameters from airborne lidar and spectral radiometer observations: the 28 October 1986 FIRE study. *Mon. Wea. Rev,* **118**, 2329-2343

10. Spinhirne, J. D., W. D. Hart, D. L. Hlavka, 1996: Cirrus infrared parameters and shortwave reflectance relations from observations, *J. of Atmos. Sci*., **53**, 1438-1458.

11. Holben BN, Eck TF, Slutsker I, Tanre D, Buis JP, Setzer A, Vermote E, Reagan JA, Kaufman YJ, Nakajima T, Lavenu F, Jankowiak I, Smirnov A, 1998: AERONET - A federated instrument network and data archive for aerosol characterization. Remote Sensing of Environment **66**: (1) 1-16.

12. Grund, C.J. and E.W. Eloranta, "The University of Wisconsin High Spectral Resolution Lidar", Optical Engineering, 30, 6-12, 1991.

9.0 Acronyms

ACE	Arctic Clouds Experiment
ACLS	Advanced Cloud Lidar System
AEROCE	Aerosol/Ocean Chemistry Experiment
AERONET	Aerosol Robotic Network
AIRS	Atmospheric Infrared Sounder
ARM	Atmospheric Radiation Measurement Program
ARMCAS	Arctic Radiation Measurements in Column Atmosphere-surface System (beaufort Sea, Alaska, June 1995)
ASTEX	Atlantic Stratocumulus Transition Experiment (Azores, June 1992)
AVHRR	Advanced Very High Resolution Radiometer
AVRIS	Airborne Visible / Infrared Imaging Spectrometer
CALS	Cloud and Aerosol Lidar System
CAR	Cloud Absorption Radiometer
CEPEX	Central Equatorial Pacific Experiment
CPL	Cloud Physics Lidar
CRYSTAL	
DAAC	Distributed Active Archive Center
DLT	Digital Linear Tape
EAL	Elevated Aerosol Layer
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
FIRE	First ISCCP Regional Experiment (California, June-July 1987; Beaufort Sea, Alaska, April-June, 1998)

GLAS	Geoscience Laser Altimeter System
HSRL	High Spectral Resolution Lidar
ISCCP	International Satellite Cloud Climatology Project
LITE	Lidar In-space Technology Experiment
MAS	MODIS Airborne Simulator
MAST	Monterey Area Ship Tracks Experiment (Monterey California, June 1994)
MODIS	Moderate Resolution Imaging Spectroradiometer
SAFARI	South African Fire Atmosphere Research Initiative
SDM	Scheduling and Data Management System
SUCCESS	Subsonic Aircraft Contrail and Cloud effects Special Study (April – May, 1996)
WINCE	Winter Cloud Experiment